ECONTECHMOD. AN INTERNATIONAL QUARTERLY JOURNAL – 2015, Vol. 04, No. 2, 45–50

The Influence of Dynamic Characteristics of Vehicles on the Passenger Car Equivalent and Traffic Delay

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ReceivedJune 08.2015; accepted: June 30 2015

Abstract. The analysis of transportation flow and technical condition of cargo-carrying vehicles and buses has showed the need in the research of its influence on the passing density on signalized intersections. The indicator which reflects this influence is represented by light motor vehicle passenger car equivalent (PCE). The need in determining a passenger car equivalent for differently structured transportation flows is demonstrated not according to the recognized methodology, but according to the one developed by the authors which takes into account both diverse structure and the level of technical condition of road users. The latter one decreases launching dynamics of vehicles which depart from the stop line. The respective passenger car equivalents are determined for such a structure of traffic flow. These calculations differ from already known and normative ones. Due to the simulation (the VISSIM program) of passing at an intersection with the use of calculated passenger car equivalents which take into account the technical condition of vehicles, traffic delays on the main direction were defined as decreased by 7.6% for respective duration of permissive signal on a traffic light.

Key words: passenger car equivalent (PCE), traffic delay, traffic light cycle, saturation flow, vehicle, technical condition, speedup.

INTRODUCTION

Nowadays we can observe rapid growth of the number of vehicles in street and road network (SRN) of cities and towns. The increase in the level of motorization, when SRN, actually, is not expanded and improved, results in problems with traffic management. Oversaturation of urban roads with cars causes queues at intersections, particularly signalized ones, which have low capacity in comparison with other elements. Consequently, drivers and passengers of public transport are additionally irritated, transporters get lower incomes, expenses of individual cars are higher, the ecology of urban air basin is being deteriorated.

It is known that light motor vehicles with high indicators of drag-out dynamics dominate in the urban traffic flows (TF). However, along with these vehicles there is a certain portion of buses and cargo-carrying vehicles with significantly lower indicators. Substantial heterogeneity of TF can be observed both in time (at hours of a day – rash hours or periods between them) and in space (in any transportation district of a city or town). Diversity of vehicles in traffic flows is taken into account with the help of respective PCEs (light motor vehicle ones), in the basis of which there are dynamic dimensions. However, the question with which dynamic characteristics and technical condition those equivalents are determined remains unanswered.

ANALYSIS OF THE LATEST FINDINGS AND SCIENTIFIC PUBLICATIONS

Both Ukrainian and foreign scientists try to find the best possible (by certain criteria) ways of passing at signalized intersections. The majority of them present TF as an ideal (by dynamics and technical condition) total of vehicles. However, reality proves the following: along with light motor vehicles there are buses and cargo-carrying vehicles which have much lower drag-out and speed properties than light motor vehicles. In our view, not to take this into account would be wrong.

In their researches [1-3] the authors point out that, when searching for the optimal managing of traffic light objects, it is necessary to take into consideration dynamic properties of vehicles which mainly determine capacity of signalized intersections. In his work, Kolesnikov O. Ye. considers an accidental character of TF formation, technical properties of a vehicle, and defines the speed, time and disposition of the first car after switching on the green light according to the formulae:

$$V = \frac{V_{\max}}{1 + D \cdot e^{-r \cdot t}}, \qquad (1)$$

$$\tau_1 = \begin{cases} 0, & if \quad t \le \Delta T \\ t - \Delta T, & if \quad t > \Delta T \end{cases}, \qquad (2)$$

$$S_1 = S_{01} + \int_0^{\tau_1} V_1 d\tau, \qquad (3)$$

where: $V_{\max}$ – maximal speed of different vehicle brands, m/s; $D = \frac{V_{\max} - V_0}{V_0}$; V_0 – initial speed, m/s; r – proportionality factor that depends on speed properties of cars, s^{-1}; τ_1 – the duration of movement of the leading car via an intersection, s; t – initial time after switching on the green light, s; ΔT - threshold of time changes t; S_1 – position of a vehicle relative to an intersection at the moment of time τ_1, m; $S_{01} = -5$ – initial position of a car relative to an intersection line when $\tau_1 = 0$, м; V_1 – car speed which depends on the time of traffic reduction at an intersection, m/s.

One of main indicators which is considered in calculation of traffic light cycle parameters is saturation flow. In works [4-5] the attempt has be made in order to take into account the composition of a traffic flow when this indicator is defined. In our view, this assumption is not quite right since saturation flow is an indicator which characterizes SRN. Nevertheless, two adjusting factors included into the formula for calculating saturation flow are provided in the Highway Capacity Manual 2000 [6] (American guidelines for the design of controlled intersections) and take into account the presence of cargo-carrying vehicles in TF and obstacles created by buses.

The main parameter of traffic, which is included into all engineering calculations, is TF intensity. Nowadays there are numerous approaches to defining passenger car equivalent. Among them we can distinguish the following ones: those used in researching TF on road spans between intersections and those used for calculating traffic light cycles at signalized intersections with different types of road crossing [7]. Numerical values of the passenger car equivalent in Ukraine are presented in the Building Code 2.3-4-2007 «Auto-roads» [8]. Values of these equivalents were defined 30 years ago and thus, cannot adequately reflect realities of today's traffic conditions. Many scientists [1-2, 9-10] state that those calculations are unacceptable for defining parameters of traffic light signaling. However, they are used in various investigations connected with designing (improvement) of SRN, management and regulating of traffic, passing intersections by vehicles, etc. For different types of vehicles these coefficients vary from 0.5 to 3.0 (motorcycle – bus).

The investigation of passing signalized intersections is carried out in different countries around the world and there is a number of findings. Thus, scientists Vrubel Yu. A. (the Republic of Belarus) [1] and Sosin Ya. (the Republic of Poland) [11] have gained nearly the same values of passenger car equivalents which differ from the ones defined by the Building Code, particularly concerning motorcycles and cargo-carrying vehicles (the scientists: PCE = 0.6-1.6, the Building Code: PCE= 0.5-2.0), buses and trolleybuses – 1.7-2.0 and 3.0 respectively (the Building Code doesn't provide these data for trolley-buses). The results of investigations carried out in England, Germany [12] and the USA [6] are also known. English scientist Webster F. V. [13], for instance, calculates this PCE within the boundaries of 0.33-2.25; Branston D. [14 – 15] – 0.15-1.68; American researchers [6] suggest mediated value of 2.0. Detailed analysis of findings by these scientists can be found in works [7, 16], and the results concerning calculations of PCEs are presented in table 1.

The following correlation is in the foundation of investigations of PCE for signalized intersections:

$$K_{pce} = \frac{t_i}{t_{lig}}, \qquad (4)$$

where: t_i – time span between vehicles of i-type during pass-by of the queue on the green signal of a traffic light, s; t_{lig} – time span between light motor vehicles during pass-by of the queue on the green signal of a traffic light, s.

Modern scientists suggest their own, justified in a certain way, PCEs which, in their view, reflect today's traffic flows in the most adequate way. However, they do not take into consideration changes in drag-out and braking properties of vehicles of different types and duration of service. The attempt to take into account technical and operational characteristics of a vehicle when defining light motor vehicle PCE has been made in [17], however, this methodology concerns road passes, and not signalized intersections.

OBJECTIVE

Despite obtained, so called final, values of light motor vehicle passenger car equivalents for TF which passes a signalized intersection, the issue concerning the technical condition under which these equivalents were defined remains open to investigations. During the operation of cars, the indicators of their drag-out and braking dynamics decrease. Respectively, the presented equivalents cannot adequately reflect the condition of TF which includes worn vehicles. The results of calculations of traffic light cycle indicate formation of excessive queues and increasing of delays on specific approaches to an intersection where there are such vehicles. In this regard, the need to develop the methodology of defining light motor vehicle passenger car equivalents which would take into consideration changes of dynamic properties of vehicles with the growth of their cumulative operational kilometers.

Table 1. Light motor vehicle passenger car equivalent

Vehicle type	Light motor vehicle passenger car equivalent to according to different authors				
	Webster	Branston	Sosin	Vrubel	The Building Code B.2.3-4:2007
Motocycles	0.33	0.15	0.6	0.7	0.5-0.75
Cargo-carrying vehicles with elevating capacity:					
to 2 tons	-	-	-	-	1.5
over 2 to 6 tons	1.75	1.35	1.6	1.4	2
over 6 tons	1.75	1.68	-	-	2.5-3.5
Tractor-trailer units	-	-	2.8	2.3	3.5-6.0
Buses	2.25	1.65	1.7	2.0	3.0
Trolley-buses	-	-	-	2.0	-
Articulated buses (trolley-buses)	-	-	2.8	2.6	-

MAIN RESULTS OF THE RESEARCH

It was previously theoretically grounded and practically confirmed that with the duration of service [18] and increasing of cumulative operational kilometers [19] drag-out and speed properties of cargo-carrying vehicles decrease. It was determined that in five years of intense exploiting they can deteriorate by 25%. This, in its turn, decreases runway speed, particularly initial one during launching from a stop line to the green signal of a traffic light. To calculate PCEs which take into account the influence of this factor the correlation (4) is suggested. Time spans between vehicles (t_i, t_{lig}) were determined according to a regressive model which takes into consideration the counting number of a car in a queue. It is the following for various vehicles:

$$t_{i,\ lig} = \beta_0 + \frac{\beta_i}{n}, \qquad (5)$$

where: β_0 – an intercept term of a regressive model which characterizes the value of a time span between vehicles for a respective saturation flow, s; β_i – the parameter of a regressive model which takes into account the deviation of a time span of a vehicle of *i*-type in the queue from the one typical of saturation flow, s; n – a variable which corresponds to a number of a vehicle in a queue.

To research time spans t_i between vehicles, the VISSIM programmed product designed for microscopic traffic simulation was used. With its help the traffic lane with a stop line (traffic light) was simulated. Firstly, the movement of TF with 100% of light motor vehicles was simulated, then – with 100% of cargo-carrying vehicles (which in the Building Code B.2.3-4:2007 correspond to the carrying capacity of 6-8 tons) with various technical conditions expressed in the simulation through launching speedup which was changed within the limits of 0.25-3.5 m/s^2 in increments of 0.25 m/s^2.

The analysis of obtained results is carried out in the MATLAB program. Using the formula (5), values of time spans between vehicles in all simulated TF were obtained. It was found that the time span of passing by of a queue of light motor vehicles is 1.53 s; of cargo-carrying vehicles it varies from 2.061 s (for vehicles with the speedup of 0.25 m/s^2) to 6.337 s (for vehicles with the speedup of 0.25 m/s^2). As a result, passenger car equivalents which take into account the technical condition of a vehicle were defined (table 2).

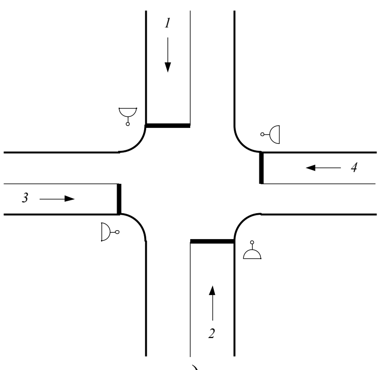
From the information stated above it is evident that PCE according to physical content is not constant but variable in functional dependence on changes of decrease in dynamic properties of cargo-carrying vehicles and buses due to the deterioration of their technical condition. This confirms its physical nature: the lower vehicle dynamics is, the higher value of PCE to a light motor vehicle will be and vice versa.

The suitability of obtained PCEs for use in defining of such an important indicator as traffic delay at a signalized intersection was verified with the help of the VISSIM product. With this aim, first of all, the simulation of a signalized intersection was created (its scheme is depicted in fig.1). Four experiments were carried out: the 1st one – all directions have 1x2 road lanes, the duration of the traffic light cycle is 65 s; the 2nd – the major way has 2x2 road lanes (flows 1 and 2 are shown in fig. 1), and the minor one with 1x1 road lanes (flows 3 and 4 are depicted in fig. 1), the duration of the traffic light cycle is 60 s; the 3rd one is the same as the 2nd one, but with the traffic light cycle of 65 s; the 4th experiment is analogues to the 3rd one, however, with the traffic light cycle of 70 s.

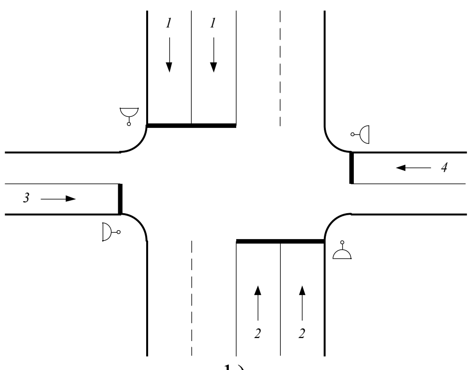
The TF saturation at an intersection was varied from 400 veh./h to 700 veh./h for the major direction (No. 1, 2, table 3) and from 100 veh./h to 300 veh./h for the minor direction (No. 3, 4, table 3) (in increments of 100 veh./h). The structure of TF was also changeable: the portion of cargo-carrying vehicles in the TF in the major direction varied from 25% to 40%, of light motor vehicles – from 75% to 60% respectively, in increments of 5%.

Table 2. Passenger car equivalents which take into account changes of dynamic characteristics (deterioration of the technical condition) of vehicles (cargo-carrying vehicles and buses)

Vehicle speed-up, m/s^2	0.25	0.50	0.75	1.00	1.25	1.50	1.75
PCE	4.14	2.88	2.35	2.04	1.83	1.72	1.63
Vehicle speed-up, m/s^2	2.00	2.25	2.50	2.75	3.00	3.25	3.50
PCE	1.58	1.52	1.47	1.44	1.40	1.37	1.35



a)



b)

Fig. 1. Simulation of a signalized intersection with road lanes 1x1 in all directions (a), 2x2 in the major direction and 1x1 – in the minor one (b)

The major direction was occupied by light motor and cargo-carrying vehicles, the minor one – only by light motor vehicles. To simplify the simulation left wheeling was banned in all ways, and right wheeling flows constituted 8% of incoming intensity. The road lane width in the major direction was 5m, and in the minor one – 3.5m. The calculations of the duration of the green signal of a traffic light were performed using PCE suggested by O. H. Levashev [10] and PCEs which take into account variation of vehicle dynamic properties (deteriorating of their technical condition) (see table 2).

Duration of traffic delays at an intersection was obtained through the simulation of TF in VISSIM. The sample of the simulation for TF which consisted of 75% of light motor and 25% of cargo-carrying vehicles (buses) (the 3rd experiment, with the duration of traffic light cycle of 65s) is shown in table 3 (the results of the first experiment are provided in the work [20]).

The figure 2 depicts the diagrams (traffic intensity in the major direction is 600 veh./h) which reflect decrease in delays in the major direction (fig. 2, a, b, c) and their increase in the minor one (fig. 2, d, e, f).

The analysis of all results of TF simulation obtained in 192 experiments and shown in table 3 has enabled establishing characteristic decrease in the duration of traffic delays in the major direction and their unsubstantial increase in the minor one (fig. 2). Data for the 3rd experiment for fig.2 are framed in bold in table 3. The TF intensity in the major direction was 600 veh./h. It was found that for all 192 variants of combinations of TF intensity in a major and minor directions, the duration of vehicle delays in the former one decreases by 7.6% in comparison, if passenger car equivalents according to Levashev are used. At the same time, it is observed the increase in delays in the minor direction by 7.1%. Total delay of all vehicles at an intersection drops by 3.6%.

Obtained results show that if suggested passenger car equivalents are used for determining the time of displaying green signals, traffic delays in the major direction decrease and in the minor one vice versa, i.e. increase. In our opinion, such a situation can be considered as an acceptable one since it creates an advantage for a major (through) road, which, as a rule, is occupied by much higher amount of public transport. And delays of this transport are not allowed in order to comply with traffic schedules. In the variants of combining N_{maj} and N_{min} for 192 experiments, the former one exceeded the latter one by 1.2-7.0 times.

When obtained results are used, the duration of permissive signals on the major (through) direction of TF movement will need corrections.

CONCLUSIONS

1. The analysis of a structure of traffic flows and technical condition of vehicles proved the necessity of investigating its influence on the dynamics of passing signalized intersections. The indicator which reflects this influence was decided to be light motor vehicle passenger car equivalent.

2. Through the simulation of passing by TF of different structure (light motor and cargo-carrying vehicles, buses) a signalized intersection with a major (through) and minor roads which have different traffic intensity (the former one has higher by 1.2-7.0 times intensity than the latter one) the following data has been obtained: for all 192 variants of combinations of TF in a major and minor directions, the duration of vehicle delays in each experiment decreases by 7.6% on average in comparison, if traditional passenger car equivalents are used. At the same time, the increase in delays on the minor direction by 7.1% is observed Total delay of all vehicles at an intersection drops by 3.6%.

Table 3. Duration of traffic delays according to the results of the simulation

№ ТП	TF intensity in the major direction, N_{maj} ,veh./h	TF intensity in the minor direction, N_{min}, veh./h					
		100		200		300	
		Passenger car equivalents					
		acc.to Levashev	suggested	acc.to Levashev	suggested	acc.to Levashev	suggested
		Delay, s					
1	400	8.13	7.72	13.98	13.33	18.35	17.63
2		8.33	7.73	14.75	13.98	19.62	18.68
3		14.82	15.57	9.33	9.92	7.00	7.48
4		13.75	14.42	9.60	10.15	7.85	8.37
1	500	7.00	6.62	13.33	11.78	17.97	16.55
2		6.92	6.33	13.10	11.52	17.60	15.92
3		17.27	18.02	11.13	12.40	8.52	9.63
4		15.83	16.55	11.40	12.65	9.43	10.60
1	600	6.52	5.92	11.60	11.02	16.23	15.38
2		6.37	5.82	11.50	10.95	15.98	15.03
3		18.80	19.57	13.00	13.65	10.18	10.82
4		17.35	18.13	13.33	14.02	11.20	11.78
1	700	6.27	5.60	11.07	10.52	15.65	14.18
2		5.62	5.15	11.13	10.40	15.50	13.97
3		20.37	21.18	14.33	15.07	11.45	12.70
4		18.95	19.73	14.70	15.40	12.43	13.77

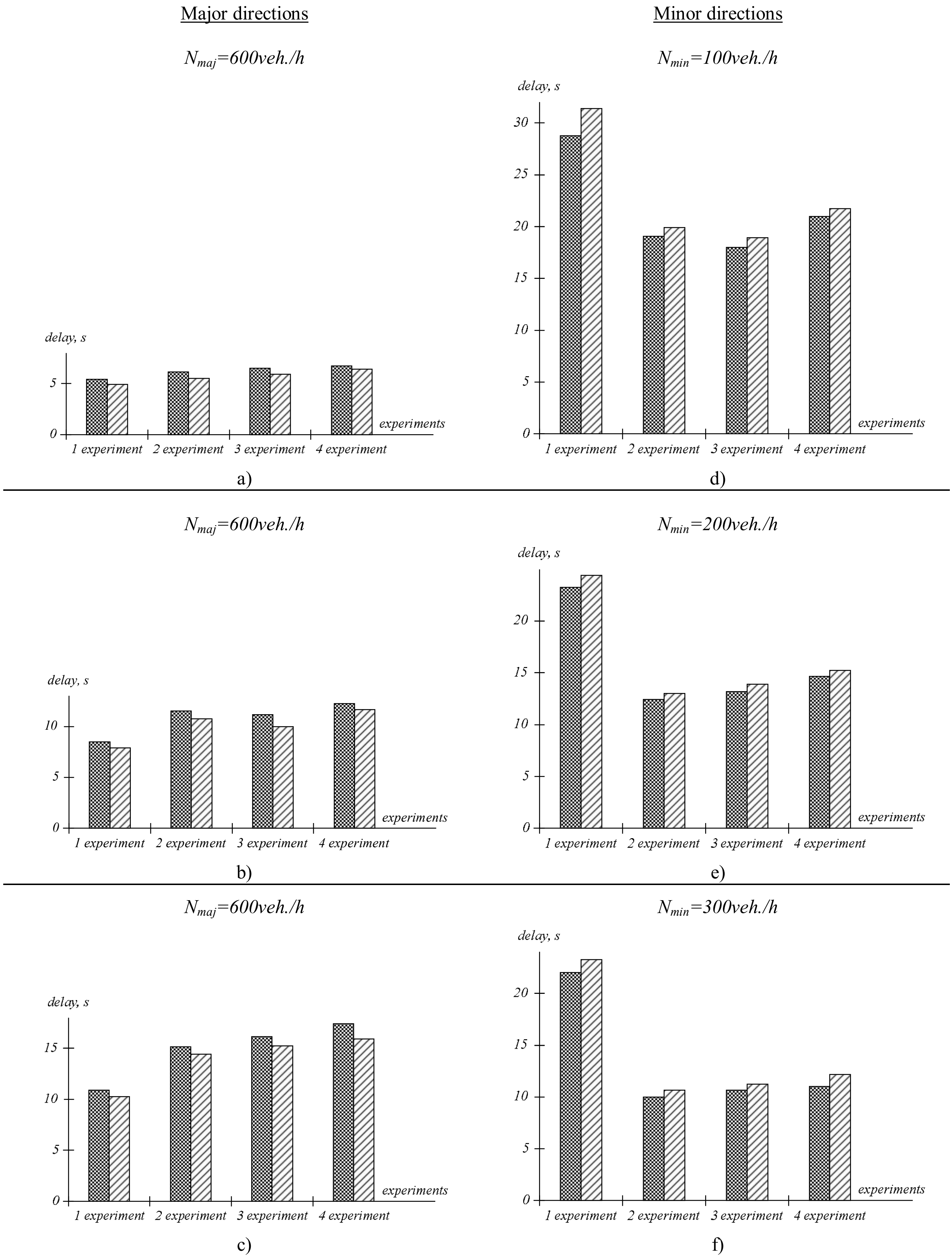


Fig. 2. Changes of the duration of traffic delays in the traffic flow at a signalized intersection consisting of 75% of light motor vehicles and 25% cargo-carrying vehicles and buses: ▩ – using passenger car equivalents according to Levashev; ▨ – using passenger car equivalents which take into account reducing of dynamic properties of a vehicle

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